Thermal Stress for TPC Wires During Cooldown of Micro-Boone

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TPC wires and Tensile Stress

- Wire Material: SS 304 V by Fort Wayne Metals
- Mechanical Property: ~ 95% cold work, 280,000 psi (280 KSI), Yield Stress, 334 KSI U.T.S. per catalog
- 292 KSI Y.S., 341 KSI U.T.S. on spool label

- Wire dia. 150 x 10^{-6} m, +/- 5 micro-meter
- Cross section area A ~ pi / 4 d^2 ~ 1.767 x 10^{-4} cm^2
- For 1 kg load, stress = load / area ~ 5660 kg/cm^2, or 80,325 psi (80 KSI)
- For 0.7 kg load, stress = 56 KSI
- and 3 kg => 241 KSI, 4 kg => 321 KSI (beyond Y.S.)

Thermal Stress in TPC wires

- Modulus of Elasticity: 28.5×10^3 KSI
- Thermal expansion of SS304 from 300 to 80 K equals ~ 0.003 (in reasonable agreement with micro-boone experience on SS304V) => Thermal stress (between 300 and 80 K) ~ 85 KSI
- Thermal expansive coefficient equals ~ 15.3×10^{-6} in/in/K near room temperature.
- For 20 K temperature difference, thermal expansion equals ~ 0.00031 corresponding to ~ 8.7 KSI
- For 50 K temperature difference, thermal expansion equals ~ 0.00077 corresponding to ~ 22 KSI
- For 100 K temperature difference, thermal expansion equals ~ 0.0015 corresponding to ~ 44 KSI

Property of SS304 V Wire - Fort Wayne Metals

304V

Melt Practice

This austenitic stainless steel is initially electric-arc melted. Then as a refinement to the purity and homogeneity of the metal, 304V is Vacuum Arc Remelted (VAR). This process yields a more uniform chemistry with minimal voids and contaminants.

Typical Chemistry

	FWM Avg. Wt. %	ASTM A313-95
Chromium	18.58	18.0-20.0
Nickel	8.65	8.00-10.50
Carbon	0.073	.08
Manganese	1.310	2.00
Molybdenum	.16	-
Silicon	0.70	1.00
Phosphorus	0.021	.045
Copper	.17	-
Cobalt	.10	-
Nitrogen	.034	.10
Iron	Balance	Balance

FWM chemistry is for reference only, and is not to be used for specification purposes.

Physical Properties

Density	0.286 lbs/in^3
Modulus of Elasticity	28.5 psi x 10^6
Electrical Resistivity	720 µohms-mm
Thermal Conductivity	16.36 W/m K (100°C)

Applications

This alloy is the most popular for medical appliances. The ease of joining with solder or welding, combined with excellent strength makes it desirable. This alloy is also one of the least expensive medical materials. Some examples of end products are stylets, catheters, guide wires, springs and needles. Fort Wayne Metals routinely makes cables, strands, flat wire and shapes from this alloy.

Mechanical Properties

% CW	Y.S. (psi)	U.T.S. (psi)	% Elongation (10" gage length)
0%	50,000	107,000	41%
20%	70,000	140,000	14%
37%	90,000	184,000	4%
50%	140,000	208,000	3%
60%	160,000	229,000	2.6%
68%	180,000	247,000	2.7%
75%	200,000	265,000	2.6%
80%	215,000	272,000	2.9%
84%	230,000	289,000	2.5%
90%	245,000	306,000	2.6%
93%	250,000	316,000	2.7%
95%	280,000	334,000	2.6%

Values are typical and may not represent all diameters. Test method will affect results.

Surface Conditions

Label on Wire – Fort Wayne Metals

Yield Stress: 292 KSI
Ultimate: 349 KSI

Estimation of Tensile Stress in Wire

- Wire dia. 150 x 10^{-6} m, +/- 5 micro-meter
- Cross section area A ~ pi / 4 d^2 ~ 1.767 x 10^{-4} cm^2
- For 1 kg load, stress = load / area ~ 5660 kg/cm^2, or 80 KSI
- For 0.7 kg load, stress = 56 KSI
- and 3 kg => 241 KSI, 4 kg => 321 KSI
- Experience cable failed at point near the end where it is twisted (for example docdb #1780). In principle that can be evaluated from FEA modeling.
- For simple estimation, let's assume stress at failed point is 25% more than that in the middle section of wire
- Thus 0.7 kg load, could produce stress ~ 70 KSI near the "failed" point of the wire.
- Furthermore uncertainties in dia. causing area A to vary from 1 - $(145/150)^2$ to $(155/150)^2$ – 1 or 0.93 to 1.068, roughly +/- 7%. So will the stress.
- Thermal stress (between 300 and 80 K) => 85 KSI (previous slide) (=> ~ 1 kg load for TPC wire, in reasonable agreement with 0.75 kg measurement by Bo in docdb # 139)
- The max. stress in a cable subject to (300 – 80 K thermal stress) will be ~ 155,000 ps ----- -> well below Y.S.

Max. Pre-Tension to avoid wire breakage without controlling cooldown rate

- Suppose we want to keep the max. stress below 230 KSI (80% of Y.S.) including 85 KSI thermal stress.
- The max. pre-tension will be ~ (230 – 85) KSI ~ 145 KSI
- Let's assume the stress factor is 1.25 and there is 7% reduction due to some wires have "smaller" dia.,
- Pre-Tension stress in the middle of wire becomes 108 KSI (corresponding to 1.35 kg load).
- There are some safety margin due to strength of SS304V increases with reduction in temperature (probably more than 10%).
- Therefore, a comfort pre-tension is ~ 1.5 kg for wire to survive a sudden temperature change of 220 K.

Max. Pre-Tensile to avoid wire breakage with control cooldown (20 K difference)

- Let's assume the max. stress is 230 KSI (80% of Y.S.)
- Thermal stress of TPC wires with 20 K temperature difference is ~ 8.7 KSI
- The max. pre-tension will be ~ (230 – 8.7) KSI ~ 220 KSI
- Let's assume the stress factor is 1.25 and there is 7% reduction due to some wires have "smaller" dia.,
- Pre-Tension stress in the middle of wire becomes 163 KSI (corresponding to 2 kg load).
- There are some safety margin due to strength of SS304V increases with reduction in temperature (probably more than 10%).
- Therefore, a comfort pre-tension is ~ 2.2 kg for wire to survive a sudden temperature change of 20 K.

Safety Factor and Conclusion

- Since wire is not for pressure vessel, present application does not need to use the same safety factor as ASME Pressure Vessel Code.
- Safety factor could be chosen based on good engineering judgment and 80% of tensile at ambient temperature seems reasonable.

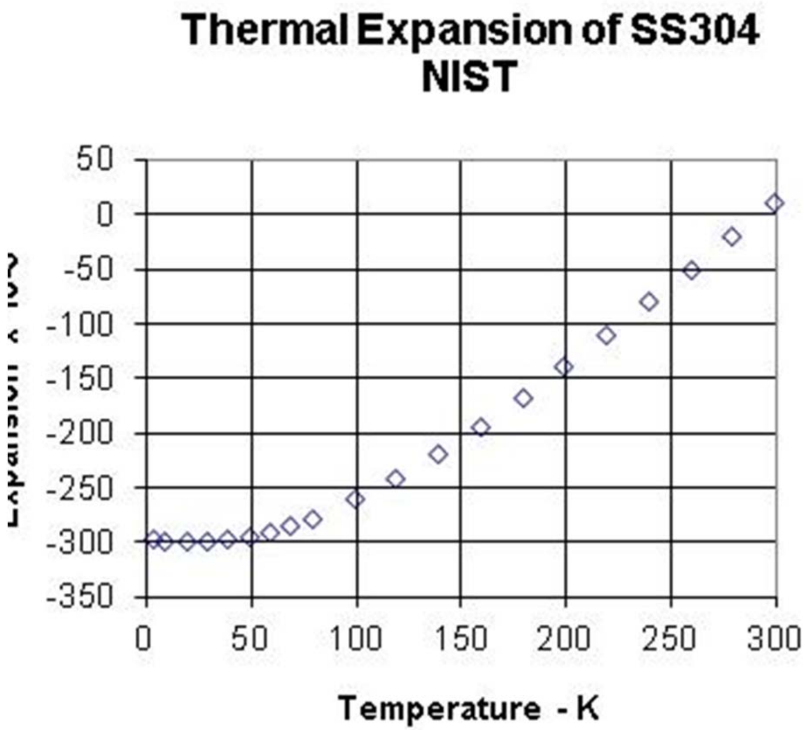
- Thermal stress is “small” in a control cooldown at 20 K and pre-tension could be as high as 2.2 kg.
- Even for larger temperature difference of 50 or 100 K, thermal stress is small compared to the Yield Stress of the SS304V wires.
- If a wire is to survive a sudden dip into LN2 bath, the max. pretension is estimated at ~ 1.5 kg
- At present, we intend to apply 0.7 kg pretension (which is well below above values) to wires. Thus, wire will not break due to thermal stress in micro-boone.

- Thermal stress in wire is a concern for cooldown only. During warm-up, the wire elongates and will not break.

Background Material and Calculations

Thermal Expansion of SS304 and Comparison with Micro-Boone Experience on 304 V Wire

Temp	Exp	Exp Coef.
K	normal	10^-6
	10^-5	1/K
300	10.86	15.5
280	-19.87	15.3
260	-50.35	15.2
240	-80.50	15.1
220	-110.2	14.8
200	-139.1	14.5
180	-167.1	14.0
160	-193.7	13.3
140	-218.6	12.4
120	-241.3	11.3
100	-261.2	10.0
80	-277.7	8.3



Use thermal coefficient of 15.3 x 10^-6 1/K, thermal expansion equals 0.00031 with a 20 K difference, 0.00077 with 50 K difference, and 0.0015 with 100 K difference. Total thermal expansion equals ~ 0.003 from ~ 80 to 300 K.

Note: Total thermal expansion between 80 and 300 K are in reasonable agreement with the measurement of 0.22% by Bo (docdb #139) and 0.27% by Fermilab (next slide).

Micro-Boone Docdb # 139

Some Wire Tension Measurements

(Bo Yu, Jan. 10, 2008)

1. Measure the tension increase to a wire with its total length fixed to simulate the sudden cooling of wires while the frame is still at room temperature.

2. Measure the integral coefficient of thermal expansion (CTE) and the Young's modulus of the wire at room temperature and LN2 temperature.

Results

Modulus of elasticity

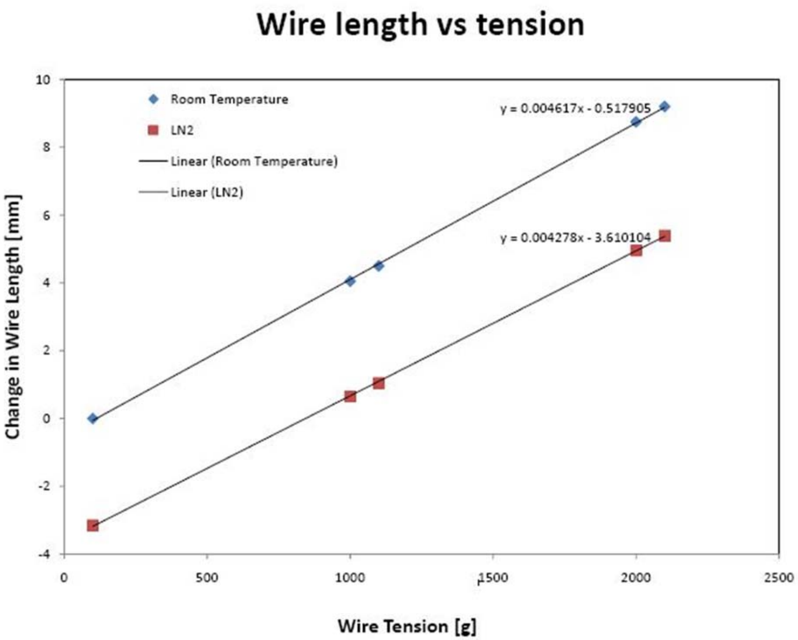
	Fort Wayne	this measurement
RT	195 GPa	170 GPa
LN2		183 GPa

Integral CTE

	FNAL	this measurement
Integral CTE	0.27% @ 87K	0.22% @ 77K

Tension increase due to sudden cooling: 0.75kg

Micro-Boone Docdb # 139



Bo's result on SS 304 V TPC wire, docdb 139						
y (mm) = a x(g) + b						
Elogation				Stress		
Epslon = y / length				Sigma = x(lb) / A(in2)		
length =	1320	mm		dia =	0.015	cm
				A =	0.000177	cm2
				A(in2) =	2.74E-05	in2
x(g) = x(lb) x 454						
x(lb) = Sigma(psi) x A(in2)						
x(g) = A(in2) x 454 x Sigma(psi)						
Epson = a x A(in2) x 454 / length x Sigma(psi) + b / length						
or						
Sigma(psi) = (Epson - b /length) / [a x A(in2) x 454 / length]						
At room temperature,						
a =	0.004617					
b =	-0.517905					
b/length =	-0.00039					
1 / (a x A(in2) / 454 / length) =			**2.30E+07**	Modulus of Elasticity		
			psi			
At LN2 temperature						
a =	0.004278					
b =	-3.610104					
b/length =	-0.00273					
1 / (a x A(in2) / 454 / length) =			**2.48E+07**	Modulus of Elasticity		
			psi			
Thermal Expansion between room temperature and LN2 temperature						
At	room temp	LN2 temp				
x	y)300 K	y)80 K	y)300K - y)80K		**Elongation**	
g	mm	mm	mm		**in/in**	
0	-0.52	-3.61	3.09		**0.00234**	
1000	4.10	0.67	3.43		**0.00260**	
2000	8.72	4.95	3.77		**0.00286**	